ロボット体表に分散配置するための集積化触覚センサに関する研究

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論 文 内 容 要 旨

In recent years, there has been great interest generated in the emerging field of social robotics. In contrast to industrial robots which work only at structured environment such as factory, the social robots work at the anthropic domains. Because social world is unstructured and contains many unpredictable movements of person, the robots has to equip more advanced sensor and cognition function. An example of general sensor and perceiving method is to use vision sensor and image recognition. For the closer interaction such as picking up persons, however, the visible information is insufficient. The invisible information such as shear force or, small vibration caused by slipping are also important for grasping an object. In the case of a human, tactile perception is one of the important sensory which assist eye sight. In physiology, the 7~ 700μm size cell called tactile receptor send a electrical pulse to brain cortex when detect small deformation of skin. There are 10^7 tactile receptors on whole body, and these cell are distributed in varied density by the region. It is known phychophysically that two points distanced by 2*mm* can be distinguish at finger tip while not at the back if the distance is below 70*mm*. The tactile sensory is very large and dense than other sensory in human body. The number of report about experimental robots which have tactile sensors on whole body has increased gradually from 1990s. Whole body tactile sensor system make it possible not only to lift an object but also to predict the meaning of the detected haptic interaction such a tapping or stroking. The candidate for artificial tactile receptor can be classified into soft and hard material. Soft tactile sensors is based on piezoelectric or piezo-resistive phenomena of elastomer film. The advantage of the soft tactile sensor are cheap, flexible and has a large area coverage, while the disadvantages are low spatial resolution and little tactile information. Hard tactile sensors contains detection circuit and structure which decompose the external force to each axis. The hard tactile sensor has a potential to sense and amplify the many physical information such as 3-axis force, torque, vibration. However, large area mounting is difficult because of the cost and its stiffness. Although the tactile interaction become expressive as tactile sensor increase, the increment of the sensor and tactile data to be processed makes it difficult to achieve the high density tactile mounting. In recent years, however, there have been moves to connected each sensors by network, especially the serial bus network reduces the number of wires drastically. Currently, the number of total mount of the artificial it is reported that the robot which has over a thousand tactile sensor is possible by means of network on the robot surface. However the circuit board is still too large to mount densely, the broad minituarization is needed to achieve human-like artificial tactile sensor.

In this study, the tactile sensor which is based on integration between silicon micromachining and integrated circuit is developed to overcome disadvantages of hard tactile sensor. The tactile sensor is fabricated by micromachining technology and it can detect the force in the range from 0 to 500gf by means of capacitance changes. The integrated circuit near the tactile sensor makes the serial network connection possible. The packaging features is also proposed in terms of costs, chip size and final feature of mounting. The proposed packaging feature is thin enough to eliminate a feeling of a foreign body, and same size with chip size, in other words, chip size packaging. These integrated and packaged tactile sensor is electrically connected on the flat serial bus cable (fig.1), then the flat cable is twisted around robots body (fig.2).The configuration of tape-like shape is suitable to mount in curved surface or movable portion.

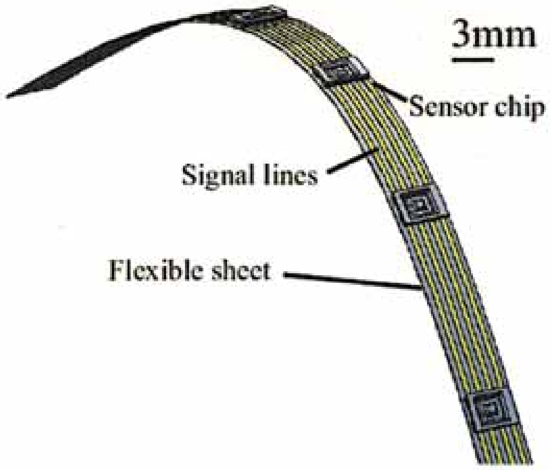

Fig.1 Integrated tactile sensor on flexible serial bus cable

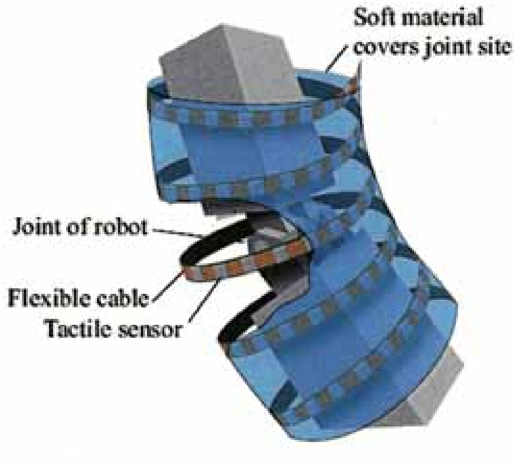

Fig.2 Twisted mounting of tactile sensor around the movable portion.

In chapter 1, the relationship between robotics and tactile and social trend of robotics are described. The phychophysics is also introduced to understand how the tactile signal transmit from receptor cell to brain cortex and how a human recognize the sensation of touch, which helps to design new tactile sensor system. The objective of this study is derived from these background.

In chapter 2, the material, structure and feature of the new tactile sensor to be fabricated experimentally are decided (Fig.3). First, the structure of the tactile sensor is strongly depends on the form of the mounting. As mentioned above, the tactile sensor chip is mounted on the flexible cable which has signal bus line. In this study, the 4-wired serial bus network is chosen as network function so that the number of wires become minimum. The requirement for the chip structure is that the sensing surface and solder pad surface has to be on the front and the back. The new tactile sensor adopts MEMS (Micro Electro Mechanical Systems) and LSI (large scale integration) integration based on wafer bonding technology. The shellcase type wafer level packaging method can realize the structure that sensing surface and soldering surface is on the both side of chip. The most important aspect of this packaging method is electrical connection from LSI pad to backside along the groove etched by TMAH. Furthermore, the outline of the fabrication process is determined among a variety of options.

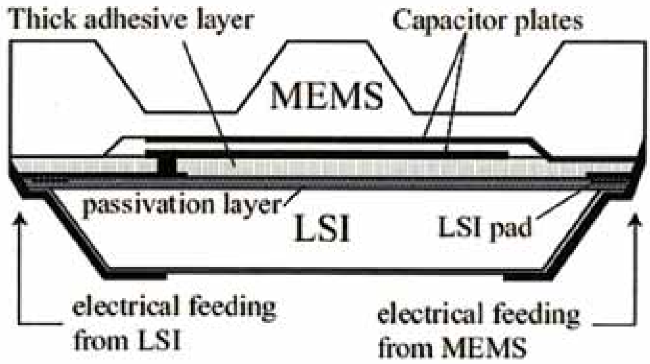

Fig.3 Cross section of the MEMS-LSI integrated tactile sensor

In chapter 3, detailed process development is described. The development includes such as choice of bonding material, coating method, patterning method, etc. The feature of this tactile sensor is using many polymer in wafer bonding or insulation layer, each polymer are evaluated on the basis of thermal and chemical stability against subsequent packaging process. Especially the polymer for adhesive layer is important, it has a function not only adhesive layer for wafer bonding but also electrical isolation layer. Benzocyclobutene (BCB) is chosen from other polymer such a epoxy, SU-8, and special product for bonding film. Void-free, uniform wafer bonding can be achieved because of its small outgassing and liquid-like behavior in curing. The chemical stability is relatively high, It is reported that the chemicals such as TMAH (Tetramethyl Amonium Hydroxide), Hydrofluoric acid, Sulfuric acid and Xylene does not attack BCB after full curing. In addition, the new coating technology had to be developed to form thick polymer layer (> 50μm).It is found that a totally new coating method is necessary to achieve the thick polymer layer, because the edge-bead effect or polymerization degree mismatch becomes more strict as the thickness increase with well-known multiple spin coating. In this study, the molding technology is introduced to coat the BCB layer in accurate thickness and good flatness. From an adhesive material for bonding standpoint, the polymerization degree is important. Infrared spectroscopy is used to investigate the polymerization degree of molded polymer for subsequent bonding process. BCB is also used as backside insulator of LSI. The main resiriction of backside insulator is process temperature, because the insulate process have to do in the last of the integration process. The spray coating of BCB is introduced to coat conformally on the backside of LSI at low temperature(< 250℃).Because the backside insulator have to stand for solder reflowing temperature, the thermal stability of BCB is suitable for insulator which is exposed are of the package.

In chapter 4, the integration and packaging process developed in chapter 3 is applied to consumable LSI to demonstrate the compatibility with completed LSI. The integrated LSI named AT1027C has three channels of differential capacitor amplifier and the dimensions of an chip is 3 ×3:5*mm*.AT1027C can connect to external EEPROM which makes possible to calibrate a range or an offset of each channel. The MEMS wafer is designed so that the silicon diaphragm can detect up to 500gf. The feature of the wafer level packaging is the possibility to operation test with physical estimation in a wafer level. The probe test environment specialized for integrated tactile sensor is developed in this chapter, which can measured output signal from tactile sensor through the probe with mechanical force estimation from flip side. After accomplishment of fabrication(fig.4) , the probe test has done in the completed wafer. From the power consumption, the LSI is running for sure. However the communication between integrated LSI and external EEPROM does not work ,which needs certain electrical connections extended from LSI pad to back side in package .Despite this failure, the LSI can detect the external force correctly except sensitivity and offset from consideration(Fig.5).

In this paper, the integration between MEMS and LSI and the wafer level chip size packaging is demonstrated. BCB polymer is chosen as a main building block because of its thermal and chemical stability, adhesive performance and suitability for molding. Mechanical etching by half-dicing provides assurance that the integration process can be use for all type of the LSI. Finally, the consumable capacitor-voltage sense amplifier LSI is integrated with MEMS force sensor and packaged in chip scale, then works as integrated tactile sensor.

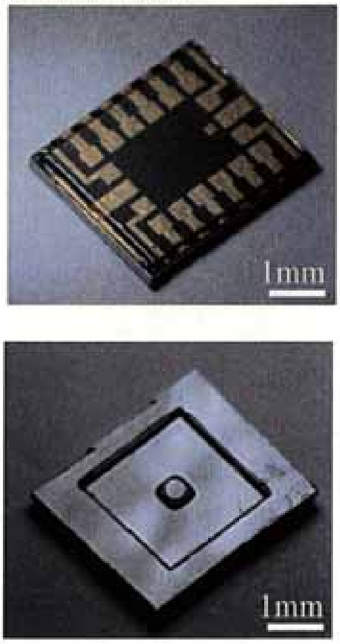

Fig.4 the back side of fabricated tactile sensor

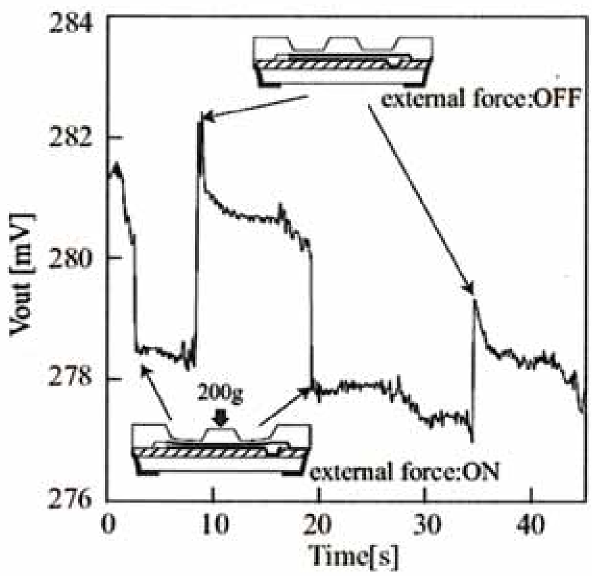

Fig.5 Response with external force of integrated tactile sensor

論文審査結果の要旨

将来，ロボットが日常生活に入り込み，人間と共存するためには，ロボットと特に人間との間の物理的接触状態を知るための触覚センサが，様々な動作の実現だけではなく，安全のためにも必須である。このような触覚センサは，その目的上，ロボットの体表全体に配置せねばならないが，場所に応じて十分な密度で配置するには，触覚センサと制御計算機との間の配線をできる限り減らすことが求められる。その解として，バス上に多数の触覚センサを接続する方法が考えられるが，そのためには触覚センサは通信機能を備え，しかも数ミリメータ四方程度以下と十分に小形でなくてはならない。

本論文は，上記のような触覚センサとして，MEMS（Micro Electro Mechanical Systems）技術による超小形触覚センシング構造と信号処理機能や通信機能を提供する集積回路（LSI）とを，ウェハレベルで集積化したワンチップセンサを提案し，その構造の設計，集積化技術の開発，および試作を行った研究結果をまとめたものであり，全編6章からなる。

第1章は序論であり，まず，次世代ロボットにとっての触覚センサの重要性，次に人間の触覚が論じられた後，過去の触覚センサに関する研究が整理され，本研究で解決すべき課題が研究目的として明らかにされている。

第2章では，ロボット体表に分散配置する触覚センサについて，センシング原理，制御計算機との通信方法，それらを具現化するセンサ構造，センサのパッケージング方法，および製作方法が具体的に提案されている。その提案とは，MEMS技術による静電容量型のSi製センシング構造と信号処理機能や通信機能を提供するLSIとを，樹脂接着層を用いてウェハレベルで接合し，また，同時にパッケージングし，ダイシングされたチップ側面を通して配線をチップ背面に引き出すというものである。この提案は，標準的なLSIを用いて超小形の集積化センサを実現できることから，有効かつ重要な概念である。

第3章では，第2章で提案した集積化触覚センサを製作するためのプロセス開発の成果が主に述べられている。Si製センシング構造とLSIとをウェハレベルで集積化するために，厚膜樹脂を用いたウェハ接合技術が開発されている。また，この接合技術を用いてセンサをパッケージングする技術も開発されている。これらの技術は，当該センサを製作するための中核技術となるだけではなく，多くのMEMSに適用しうるものであり，有効かつ重要な成果である。

第4章では，第3章で述べられたプロセス技術・パッケージング技術を用いて，実際の触覚センサを試作した結果が述べられている。試作には静電容量読出し機能を有するLSIが用いられ，提案された触覚センサが完成されている。試作した触覚センサからの応答が確認され，開発したプロセス技術・パッケージング技術の有効性が実証されている。これは重要な成果である。

第5章では，試作によって明らかにされた新たな課題が整理され，その解決方法が具体的に考察され，有効な技術が提示されている。

第6章は結論である。

以上，本論文は，ロボット体表に分散配置するための集積化触覚センサの実現方法を提案し，そのためのプロセス技術・パッケージング技術を開発し，センサの試作によって実証を行ったもので，ナノメカニクスとロボット工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。